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Measurements of the Three Components of the Water Flow around a Hydrodynamic Model in a Towing Tank with a 2D Laser Doppler Velocimeter System.

C. Couchman and D. R. Rajaona
Ecole Centrale de Nantes
Laboratoire de Mécanique des Fluides
1 rue de la noë, 44072 Nantes Cedex 03

ABSTRACT

Measuring the three components of a water flow in a towing tank can be done by using a two component Laser Doppler Velocimeter. This device is used to measure the velocity distribution and to study the boundary layer around the back half of a 1/12th scale model of a 22.5 meter fishing boat. Measurements are performed from well out of the boundary layer, in the potential flow, up to 0.5 mm of the hull, for two speeds. Some 3D stream lines are measured at the boundary layer limit.

INTRODUCTION

Experimental data dealing with 3D measurements around boat hulls in presence of a free surface are scarce. [1,2] The traditionnal techniques (hot wire or hot film, five hole pitot tube) are difficult to set up in a towing tank as in any water flow, and they always disturb the flow to be measured.

Numerical 3D viscous flow codes are useful to compute such flows, however it is often necessary to confirm these numerical results by comparison with experimental data. Furtehrmore the Navier Stokes equations are very difficult to solve when the free surface is present and when the boundary layer becomes thick, like on the afterbody of a ship whose shape creates a fairly large negative pressure gradient.

So a reliable 3D velocity measurement device, that does not disturb the flow around the model hull and that can be used on a towing tank carriage, was needed. One of the most difficult goals was the design of a small enough underwater probe to leave the measured flow undisturbed by the measuring device. The free surface is also a difficult barrier to go through without it being disturbed.

DESCRIPTION OF THE MEASURING DEVICE

Environment

The whole system is embarked on board the towing tank's carriage and must be able to do measurements under water as deep as 3 meters, around any kind of model object towed by the carriage. The usual speed range is -1 to 5 m/s for the main component of the 3D velocity and from -1 to +1 m/s for the two other components. The maximum turbulence level expected is around 50% at 1 m/s. The towing tank is 70 meters long by 5 meters wide and 3 meters deep and is equipped with a wave generator, so the measuring device must be able to collect time correlated data for measurements in unsteady flows.

Another strain on measurements in a towing tank is that the measurement time is quite short (the tank being 70 meters long, taking off the acceleration and deceleration phases, about 35 meters are left for the measurement) and in between two consecutive measurements, the experimentator has to wait for the water to calm down, -no waves, a minimum of residual turblence in the water- so as to have a good repeatability in the measurements. At 11 knots for a full scale model, about three velocity measurements can be done per hour. So a device to measure a complete velocity profile during a single run of the towing tank is essential.

Experimental procedure

The technique chosen to meet these goals is Laser Doppler Velocimetry. If the probe is well enough designed, the flow measured can be undisturbed. A real 3D LDV would have required an important under water optical arrangement to get the five or six beams to cross at the measurement volume, without even thinking of the recollection of the scattered light.

An easier solution was to use a 2D LDV system to measure the three components of the velocity by first measuring the two horizontal components, then the two vertical components by automatically rearranging the optical setup. On top of that, the best way to minimize flow disturbance was to use backscattering as recollection of the doppler signals.

The american firm AEROMETRICS in collaboration with the french firm DELTALAB designed a 2D LDV with an underwater probe. The system was tested and tuned with the help of these two firms in the Fluid Mecanics Department of the "Ecole Centrale de Nantes".

A 5 Watt Argon Laser is installed on an optical bench, the beam is separated by a prism and the blue ($\lambda = 488$ µm) and the green ($\lambda = 514.5$ µm) beams are then used in the same way. The usual speeds measured not exceding 5 m/s, grating disks mounted on electronically speed controlled motors, were chosen to introduce the frequency shift, as well as to split the beams in two. Furthermore, grating disks, unlick Bragg cells, leave the beams section circular, which is necessary with the use of fiber optics. [3] The four beams then leave the optical bench through monomode fiber optics to get to the underwater probe. (c.f. Figure 1) The four beams are focused by a 400 mm focal length lens before being reflected by a mirror to one of the sides of the probe, through a scuttle, to form the measuring volume at 440 mm from the probe axis. The mirror can be put in three different positions by an inside stepper motor so that the beam can come out of the probe either sideways, or up or downwards. This means that one can measure either the two vertical components of the velocity (u,w), or the two horizontal components (u,v).

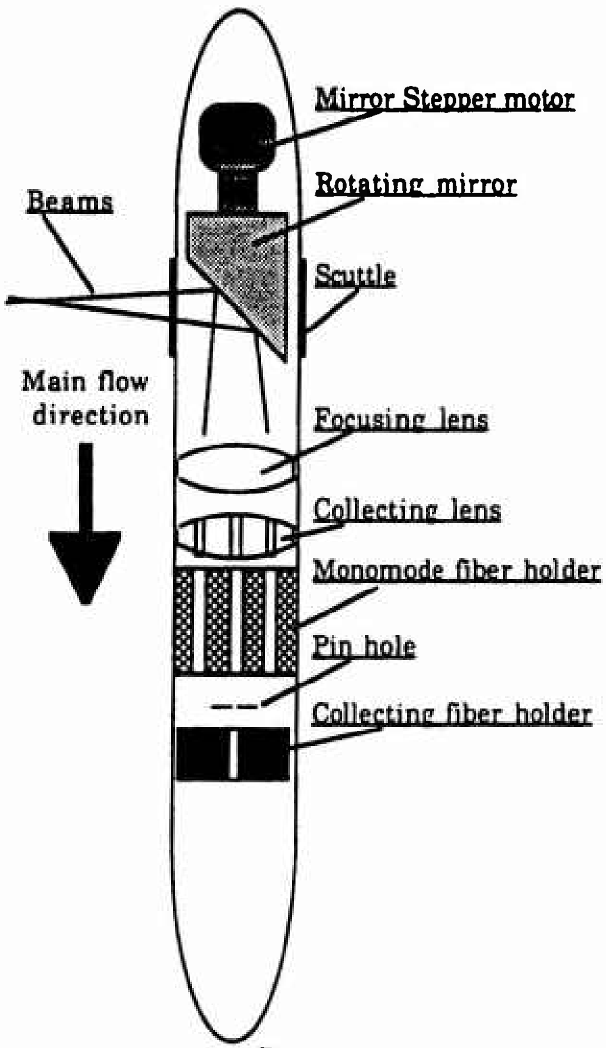

Figure 1

The measuring volume, that is the volume were the four beams cross, is 0.2 mm in diameter for 2.5 mm long.

A problem appeared when the probe was close to the surface, a wave being generated by the probe. At some carriage speeds, the side scuttle was no longer immersed, although the probe was completely under water at rest. The beams having to cross the free surface, they did not form a measuring volume anymore. This problem was solved by mounting a plate on the side of the probe.

The backscattered light reflected by the water seeding is collected through the same scuttle and passes through the two lenses to focus on a pin hole set just in front of a multimode fiber. This optic fiber is lead back to the optical bench where the two colors are seperated by another prism and sent into two photomultipliers. This probe is 570 mm long by 78x78 mm^2 section. The scuttles being in the front part of the probe, the flow around the measuring volume is not disturbed by the probe.

Seeding

Seeding is a difficult part of all LDV measurements. We have been using IRIODIN 111, a Merck nacreous paint pigment. It's density is of 2.1 in water and the particles shape resembles a coin, about 1 µm thick for 5 to 10 µm in diameter. It's color is brilliant white and it does not conglomerate in water. The particles are mixed with water and spread in the towing tank by a five tube rake,towed at low speed before the measurements. Although the seeding has a high density, it stays in the water for about three days. This allows the flow around the hull to be correctly seeded with a low turbulence level and no free surface movement.

Positionning of the measuring volume

The underwater probe is positionned by a three axis traverse system. Ball bearing screws are driven by stepper motors equiped with encoders for position checking. Any one of the three traversing axis can be equipped with another encoder whose position can be read simultaneously with the instantaneous 2D velocity. This allows to move this axis while acquiring data in a steady flow and correlate the instantaneaous velocities with the position on the axis, thus giving a 2D velocity profile in a single carriage run. Of course, in this case, turbulence information is lost. This encoder can also be mounted on a propeller shaft, so as to collect data correlated with the position of the blades, or on any kind of oscillating movement, like forced oscillations of a barge, and so on.

Data processing

The signal coming out of the photomultipliers is filtered and amplified before being analysed by a counter method. The two velocities are then collected by a computer that calculates the flow characteristics. Everything but the laser generator is controlled by the computer, allowing the experimentator to store in the data files all of the experimental conditions of the measurement.

3D acquisition

The 3D acquisition is performed by doing two consecutive 2D measurements, the mirror being rotated by 90° in between the two measurements, so as to first measure the two horizontal components then the two vertical components of the flow velocity. The experimentator can check on the component measured twice, that the flow conditions are the same. This technique does not give the complete Reynolds stress matrix, as the correlation in between all three components cannot be obtained. But comparing the velocity measured twice, usually the main component of the flow, for mean and RMS, gives the experimentator a good idea of the validity of the 3D measurement.

Characteristics

The velocity measurement being a statistic mean, the precision depends on the quality of the sample. With some practice, one can acquire about 400 2D instantaneous velocities per second, and after about 1000 samples, the mean velocity precision falls underneath 2% of the true velocity.

The whole system being controlled by the computer, frequency shifting is no longer referenced to as "frequency shifting" but as "velocity offset", this indication being easier to handle. The velocity offset range goes from 0.4 to 2 m/s on each channel.

With the side plate, measurements could be made through the side scuttle 10 mm from the free surface.

The minimum distance from a wall for a correct measurement depends on the angle at which the beams hit the wall and on the reflectance of the wall. On a wall with high reflectance -polished yellow paint- the minimum distance when the beams are tangent tp the wall is of 0.5 mm, but when the beams are perpendicular to the wall, this distance raises to 10 mm. On a wall with much lower reflectance, this last distance will be brought back down to 5 mm, but this appears to be an absolute minimum for backscattering, the measuring volume being 2.5 mm long.

The traverse system allows for positionning the measuring volume in a 90 cm x 90 cm area with a 55 cm range on the vertical axis. The position of the measuring volume is known within 0.5 mm.

MODEL EXPERIMENTAL SETUP

The model hull is a 1/12th scale of a mono propeller, 22.5 meter fishing boat presenting a transom stern. Figure 2 depicts a drawing of the underwater part of the hull. The flow was studied for two speeds, 6.9 and 11 knots.

The Froude number being respectively 0.237 and 0.377, the model Reynolds number are 1.5 10^6 and 2.55 10^6. The surface of the hull was polished paintwork, so as to have minimum surface roughness. The model was fixed on the towing tank by two rigid tubes, sliding in two fixed tubes, set one in front of the other, the boat being free to move up or down. This allows the boat to set into position while the carriage is moving. Once this dynamic position is found, the trimming of the hull being correct, the tubes are held by clamps so as to keep the boat in this position. The pitch angle is then measured.

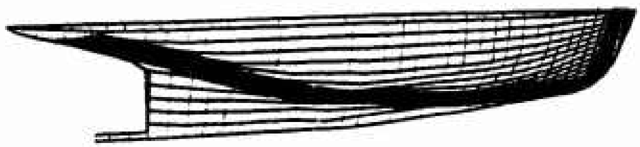

Figure 2

To reference the measuring points with respect to the hull, a known point on the hull must be detectable by the the LDV device. Then the pitch angle being known, it is easy to transform the carriage, X,Y and Z coordinates to the hull's coordinates. A reflecting tape was therefore stuck on the rear keel angle so as to be easy to find with the LDV. If the measuring volume is intersecting the reflecting tape, the filtered signal coming out of the photomultipliers is the constant frequency created by the grating disks. It is then easy to position the measuring volume on the rear edge of the keel. This point being the reference for the calculation of the measurement positions.

Only the flow on the back half of the hull was studied, the front part being easy to access by numerical codes. 2D velocity profiles along the vertical axis were done at 24 different stations. In between 2000 and 14000 instantaneous velocities are acquired to calculate each 2D mean velocity arithmetic mean. Thus turbulence information is avaliable for each of these data points. Some 3D stream lines were measured using the following technique :

(1) A starting point is chosen at about 75% of the length of the hull, just at the boundary layer limit, anywhere in between the keel line and the free surface.

(2) In two carriage runs, a 3D velocity is measured at that point.

(3) The next measurement point is calculated by moving along the velocity vector by a distance proportionnal to the velocity's intensity.

Steps (2) and (3) are repeated until the stream line exits the domain in which measurements are possible. This technique would not work in highly turbulent flows, nor in very upset flows, around corners for example, but it proved coherent in this case.

Boundary layers and scale models

Turbulent boundary layers are of course dependant on the Reynolds number and on the surface roughness of the hull. On first approach, the flow on a flat plate will give a good idea of how the viscous flow behaves to roughness and Reynolds number changes. A general law admitted for Reynolds number dependance of the boudary layer thickness is given by SCHLICHTING [4] $\delta = 0.37 * x * Re^{-0.2}$. So the boundary layer will be thicker if the Reynolds number is lower.

On the other hand, there is no simple law to discribe the boudary layer thickness dependance with surface roughness. All that can be said in general is that the boudary layer is thicker when the surface roughness is more important. When using a model boat in a towing tank, the free surface has to be taken into account by the Froude number. Thus the speed scale for towing the boat is commanded by the Froude number. $Fr = \frac{V}{\sqrt{gL}}$.
This means that if e is the scale of the model, the model's Reynolds number will be equal to the real boat's Reynolds number divided by $e{\cdot}\sqrt{e}$. Thus the boundary layer will be thicker than the boundary layer on the full size boat. But on real hulls, the surface roughness is important, this means that the boundary layer is probably thicker than given by the SCHLICHTING law. On models, the surface roughness can be chosen, giving the possibility to try and compensate the scale thickness problem.

EXPERIMENTAL RESULTS

Velocity profiles

This study was done to characterize the evolution of the boundary layer thickness on back half of the hull. The hull is flat enough for the flow to be nearly 2D when not too close to the keel nor the side. For each carriage speed, 24 velocity profiles were measured, each profile containing from 10 to 30 2D velocity measurements.

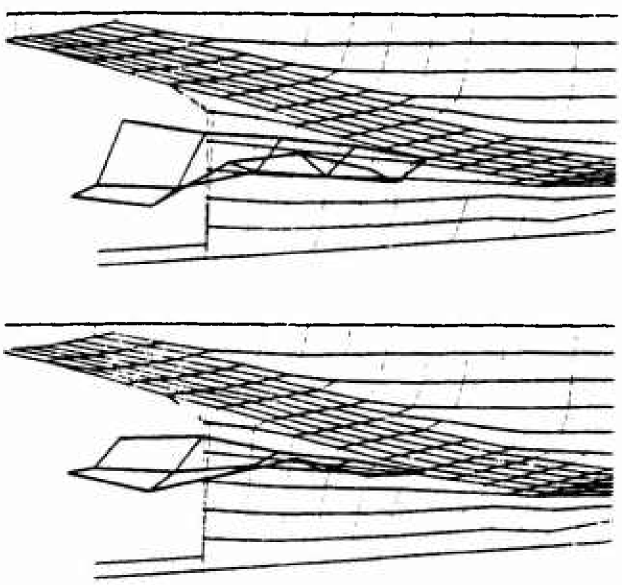

Figure 3

These profiles were made along a vertical axis on three equidistant rows, Y = 0.618 m, Y = 1.218 m and Y = 1.818 m from the hulls axis, at eight equidistant longitudinal positions, starting at X = 17.112 m from the front of the hull, and ending at X = 25.512 m. All distances being as on the real size hull. The boundary layer thickness

$$\delta_1 = \int_0^d \left(1 - \frac{U}{U_{max}}\right) \partial y$$

was calculated for each velocity profile, and figure 3 shows the boundary layer evolution on the hull. The top drawing shows the $\delta_{0.99}$ boundary layer thickness at the lower speed ($Re = 1.5\ 10^6$) and the bottom drawing shows the same parameter for the higher speed ($Re = 2{,}55\ 10^6$).
Figure 4 depicts a typical 2D velocity and turbulence level profile. The boundary layer is clearly identified by the sudden fall of the total velocity and the raise of the turbulence level. The measurement was taken near at longitudinal position x=19.512 m from the front of the boat.

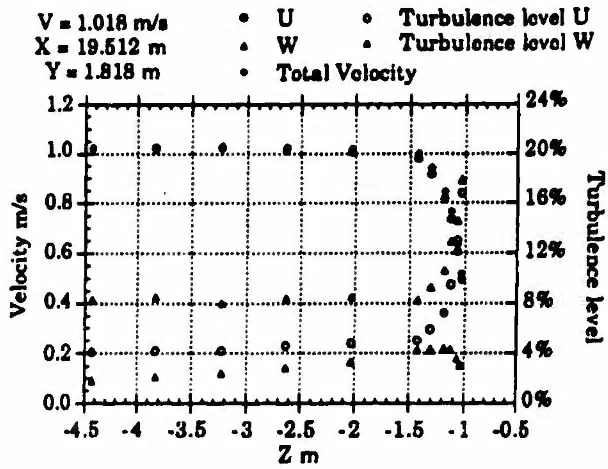

Figure 4

Knowing that the hull is at Z= -0.998 m, the boundary layer thickness can easily be measured on figure 4. It's value in this case is 0.43 m, corresponding to 35.8 mm on the 1/12th scale model. If one compares this to the flat plate boundary layer thickness law given by SCHLICHTING, $\delta = 0.37{\cdot}l{\cdot}Re^{-0.2}$ then $\delta = 34.2$ mm. This comparison comforts the idea that, as far as boundary layer thickness is concerned, the flow on the back half of a well designed hull is similar to that on a flat plate, at the same Reynolds number.It also points out a big problem in boundary flow simulation on scale models : As the free surface commands the velocity scale in between the real hull and the model, the Reynolds number on the real boat is much higher than on the model, therfore the boundary layer thickness is smaller on the real hull than on the towing tank model.
As the Reynolds number is $e{\cdot}\sqrt{e}$ times smaller on the model, the boundary layer will be $e^{0.3}$ thicker on the model than on the real boat. In our case the boundary layer on the real hull would be around 0.205 m at the figure 4 measuring point, instead of 0.43 m measured on the model. The 2.1 factor in between model and real size boundary layer thickness is important, especially that the propellor and the mobile appendices work in this area, their effect on the flow will be influenced by the too thick boundary layer, as shown on figure 3.

The non-dimensional value $\frac{U}{U_\infty}$ is plotted against $y^+ = \frac{Z}{\delta_1}$ in figure 5, compiling all of the profiles taken under the boat, at the two different speeds. It can clearly be seen that the data reduces to one single curve, much resembling the non dimensionnal velocity profile on a flat plate given by CLAUSER [5]. This shows the strong resemblance in between the flow characteristics on the hull and on a flat plate as far as the boundary layer developpement is concerned.

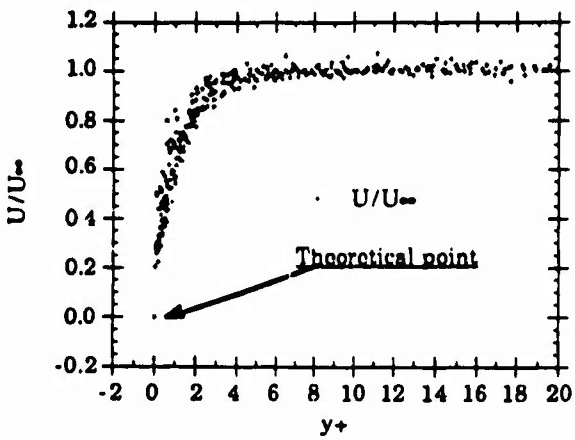

Figure 5

<u>3D stream lines</u>

Some 3D stream lines were measured starting from the longitudinal position X = 17.112 m. If M_i is a measurement point, then M_{i+1} was determined in such a way that $\overrightarrow{M_iM_{i+1}} = \alpha\overrightarrow{V_i}$ (being chosen to keep $\overrightarrow{V_{i+}}$ and $\overrightarrow{V_i}$ similar in direction and intensity. That way, the flow stream lines are correctly discribed.

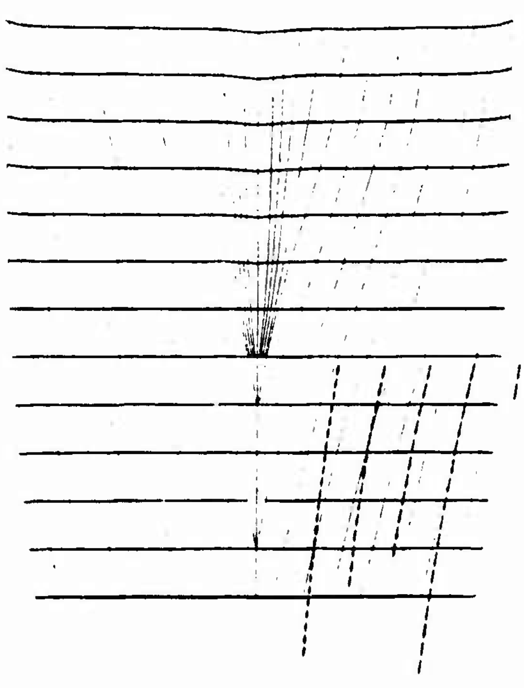

Figure 6

Figure 6 shows a 3D drawing of the back part of the hull seen from underneath. It clearly shows that this technique is applicable to the flows encountered on this kind of hulls.

CONCLUSION

This way of measuring 3D flows without a real 3D probe in the water proved to be very efficient and easy to use once the whole system is correctly tuned. The flow is undisturbed by the underwater probe, and once the seeding is mastered in the water, the data collection rate is high enough for the kind of flows we study in the laboratory. The light signal recieved by the photomultipliers is of good enough quality, even though fiber optics and back scattering are used.

These results presented here, are the first data collected with this promising measuring device. Measurements will be performed around a free hull equiped with a propeller driven by a speed controlled motor and a rudder, studying the effect of the propeller on the boundary layer thickness as well as the flow on the propeller blades. The flow around the same area of a hull, towed in a monochromatic and monodirectionnal wave, will be measured, the data being correlated to the periodic wave amplitude.

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